Results of the Prototype Camera for FACT

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Abstract

The maximization of the photon detection efficiency (PDE) is a key issue in the development of cameras for Imaging Atmospheric Cherenkov Telescopes. Geiger-mode Avalanche Photodiodes (G-APD) are a promising candidate to replace the commonly used photomultiplier tubes by offering a larger PDE and in addition a facilitated handling. The FACT (First G-APD Cherenkov Telescope) project evaluates the feasibility of this change by building a camera based on 1440 G-APDs for an existing small telescope. As a first step towards a full camera, a prototype module using 144 G-APDs was successfully built and tested. The strong temperature dependence of G-APDs is compensated using a feedback system, which allows to keep the gain of the G-APDs constant to 0.5%.

Keywords: Cherenkov telescope, Gamma-Ray Astronomy, Geiger-mode Avalanche Photodiode

1. Introduction

Imaging Atmospheric Cherenkov Telescopes (IACT) are a powerful technique for astrophysics, opening the window to photons with an energy in the order of 100 GeV to some TeV. Such photons induce Extensive Air Showers (EAS) when entering the Earth's atmosphere, and their secondary particles emit Cherenkov light. This light is collected and detected in the camera of the IACT. The camera consists of photosensors which are sensitive to single photons. Typically photomultiplier tubes (PMT) are used.

Geiger-mode Avalanche Photodiodes (G-APD) are semiconductor photosensors which have the potential to replace PMTs in many applications. The feasibility of using G-APDs in cameras for Cherenkov telescopes is being evaluated in the First G-APD Cherenkov Telescope (FACT) project. The first observation of air showers with a G-APD camera was reported in summer 2009 [1].

One of the main limitations of G-APDs is the strong temperature dependence of most operating parameters (see chapter 2.3). Therefore, the operation of G-APDs under outdoor conditions as in the camera of a Cherenkov telescope requires a compensation for temperature changes. This can either be achieved by stabilizing the temperature of the G-APDs or by actively adapting the bias voltage of the G-APDs which compensates the temperature changes. For

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the FACT camera the bias voltage is regulated via a feedback system. The feedback system and its performance are described in section 3.2.

2. Geiger-mode Avalanche Photodiodes

2.1. General information

When Einstein formulated his Nobel prize winning description of the photoelectric effect in 1905, he laid the theoretical foundation for a new field of detector physics: the measurement of light on the level of single photons. Thirty years later the theory turned into a reliable and highly sensitive device in the form of the photomultiplier tube.
A breakthrough could be expected from photosensors made from semiconductors. Besides the compactness and the increased mechanical robustness, an important advantage is the possibility to operate them in strong magnetic fields. Most running experiments using semiconductor photosensors chose PIN diodes or Avalanche Photodiodes (APD). For PIN diodes and APDs operated at small gain, the main limitation is the discrimination of small signals against the background noise. APDs can be operated at a gain up to 2000, with the problem that the excess noise factor is high [2].
The principle of operating APDs in Geiger mode to detect single photons is known for almost fifty years [3]. But only with the progress of the semiconductor technology, the design of the sensors could be improved to allow to build devices which are now known as Geiger-mode Avalanche Photodiodes (G-APD). The sensitive area is divided into an array of single cells, each with the possibility to detect single photons. The cells are connected in parallel such that the total signal of a device is the sum of the single cells.

2.2. G-APD characteristics: gain, photon detection efficiency, saturation and crosstalk

When one of the cells of a G-APD is triggered, a certain charge Q is released. The gain G is defined as this charge divided by the elementary charge e. It is proportional to the so-called overvoltage V, the difference between the bias voltage V_{op} which is applied

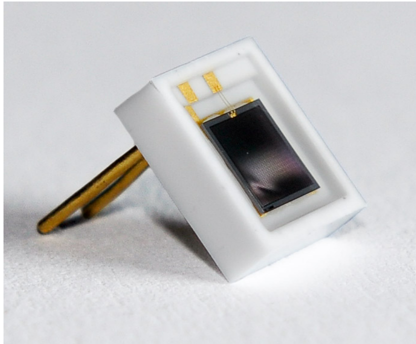

Figure 1: G-APD by Hamamatsu Photonics. The sensitive area is $3 \times 3\,\mathrm{mm}^2$ in a $6.55 \times 5.9\,\mathrm{mm}^2$ ceramics package.

and the breakdown voltage V_{bd} of the device:

$$G = \frac{Q}{e} \propto V = V_{op} - V_{bd}$$

The probability that an incoming photon triggers a cell is denoted as photon detection efficiency (PDE). It is the product of a geometrical fill factor, the probability of an electron-hole production (the quantum efficiency) and the probability that these charge carriers trigger the cell (trigger probability) [4]. While the fill factor and the quantum efficiency are fixed device properties, the trigger probability depends on the overvoltage V.
If two photons hit the same cell simultaneously, the resulting signal is the same as with only one photon. This induces a statistical saturation, if multiple photons arrive at the same time at the diode surface. The number of triggered cells $N_{triggered}$ depends on the number of incoming photons N_{inc} and the number of cells N_{cells} of the G-APD:

$$N_{triggered} = N_{cells}(1 - e^{\frac{N_{inc} \times PDE}{N_{cells}}})$$

Cells with a breakdown emit photons which in turn may trigger neighboring cells. This process is called crosstalk. Since the number of emitted photons and the probability of their detection both depend on the overvoltage, also the crosstalk probability is voltage dependent. See figure 2 for an overview of the voltage dependencies.
If a light pulse of a certain intensity is detected with a G-APD, the total released charge depends on the previously described characteristics and thus on the overvoltage V. The combined dependency (see

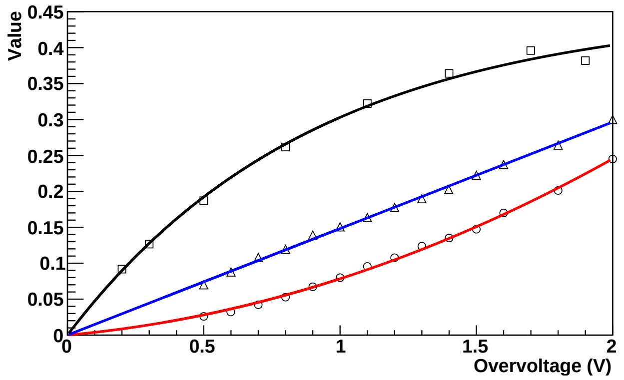

Figure 2: Dependency of the gain (blue), photon detection efficiency (black) and crosstalk probability (red) on the overvoltage. The ordinate axis units are arbitrary (gain) and probabilities (PDE, crosstalk probability).

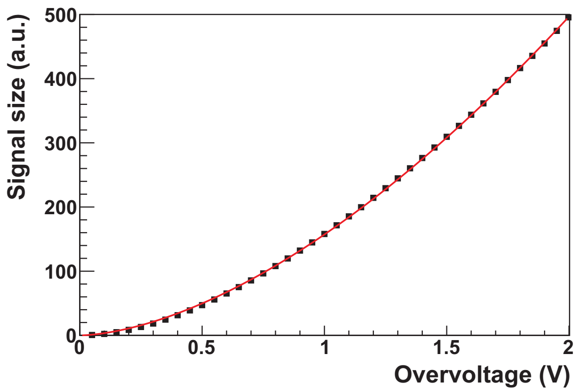

Figure 3: Calculated G-APD signal for a fixed number of 100 photons. The non-linearity is the consequence from the combined voltage dependencies of gain, PDE and crosstalk probability (see figure 2). The red line indicates a V^α fit with $\alpha = 1.66$.

eg. [5]) is completely non-linear. As an example, the resulting signal for a light pulse of 100 photons was calculated. The resulting dependency on the overvoltage is approximately proportional to $V^{1.66}$ (see figure 3).

2.3. Temperature dependence

One of the major disadvantages of G-APDs compared to PMTs is their temperature dependence. Many characteristics of the G-APD depend on the overvoltage and thus on the breakdown voltage (see section 2.2). This breakdown voltage depends on the temperature. To ensure a stable operation of the camera, the temperature dependence has to be controlled (see section 3.2). The measured temperature dependence of the breakdown voltage of our devices (Hamamatsu Photonics S10362-33-050C) is linear with $\sim$ 58 mV/K. Using the estimated dependence of $V^{1.66}$ of the pulse size on the overvoltage, the relative change of the signal size of a pulse per Kelvin is $\sim$ 9% for the standard overvoltage of 1.1 V.

3. The prototype camera module

3.1. Design

To gain experience in the operation of G-APDs under outdoor conditions with changing temperatures and background light from the night sky, a prototype camera module was built. The module consists of 144 G-APDs in groups of four G-APDs which form a pixel (36 pixels). After the amplification, the analog signals of one group are summed up and sampled using the Domino Ring Sampling (DRS) chip [6].
The camera box, which is light- and watertight, contains the photosensors, the amplifier and summation electronics as well as a water cooling system. The cooling system is for test purposes only and is not necessary for the operation of the camera. The digitization electronics is not included in the camera. A discriminator threshold is applied to the signals of the innermost 16 pixels. The trigger consists of a N out 16 majority logic on the discriminated signals of those pixels, with $N = 3 - 4$.
In summer 2009, this camera was mounted on the roof of ETH Zurich in front of a small mirror with 80 cm focal length. The single pixel discriminator thresholds were set to 4-7 pixel, resulting in single pixel rates in the kilohertz range. The resulting trigger rate after the majority logic was some Hertz. This setup allowed for the first time to record air showers with a G-APD camera. The details of the setup and the results of the observation can be found in reference [1].

3.2. Temperature compensation

To account for temperature changes during the night, a feedback system was implemented in the prototype camera. LEDs which emit short light pulses were integrated into the side of the entrance window (see figure 4). The pulses are registered by

the G-APDs and processed in the standard readout chain. The reconstructed pulse size is compared to a reference value and the bias voltage adjusted if necessary to keep the overvoltage at a constant value.

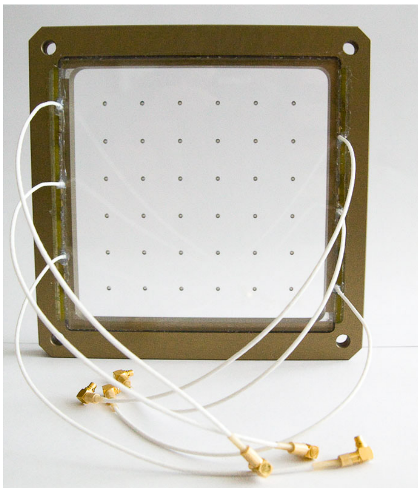

Figure 4: Entry window of the prototype camera module. LEDs are integrated of the side of the window to provide light pulses for the feedback system.

3.3. Performance of the feedback system

The performance of the feedback system was tested in an overnight run. The test was divided into two phases: in the first phase, the feedback system was deactivated, only the pulse sizes were recorded. Due to the rising ambient temperatures by 12.4 K, the measured pulse intensities were reduced by a factor of four. For the second phase, the feedback system was activated which regulated the bias voltage until the pulses were at their nominal size. Changes in the temperature were continuously tracked with the bias voltage (see figure 5). The feedback system kept the pulses and thus the gain stable within 0.5 percent. The details of the feedback system and its performance are described in reference [7].

4. Outlook: the FACT project

The successful tests with the prototype module are a first step towards a full camera for a Cherenkov telescope. The FACT camera will have 1440 pixels, each consisting of a single G-APD and a light collecting cone [8]. For the trigger, the analog G-APD signals are summed up in patches of 9 and a discriminator threshold applied to the summed signal. The signals are digitized using the Domino Ring Sampling chip DRS4. The assembly of the camera is planned in autumn of 2010. The first operation of the camera on a Cherenkov telescope is scheduled for the winter 2010/2011.

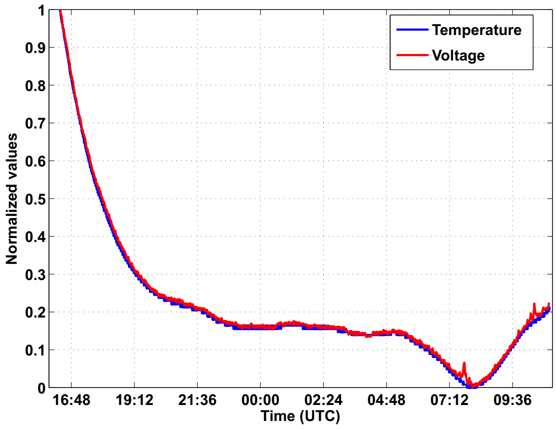

Figure 5: Changes in the ambient temperature are recognized by the feedback system via the light pulser (see section 3.3), whereupon the bias voltage of the G-APDs is adapted to compensate the temperature change.

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